

Study QCD Phase Structure in High-Energy Nuclear Collisions

Nu Xu

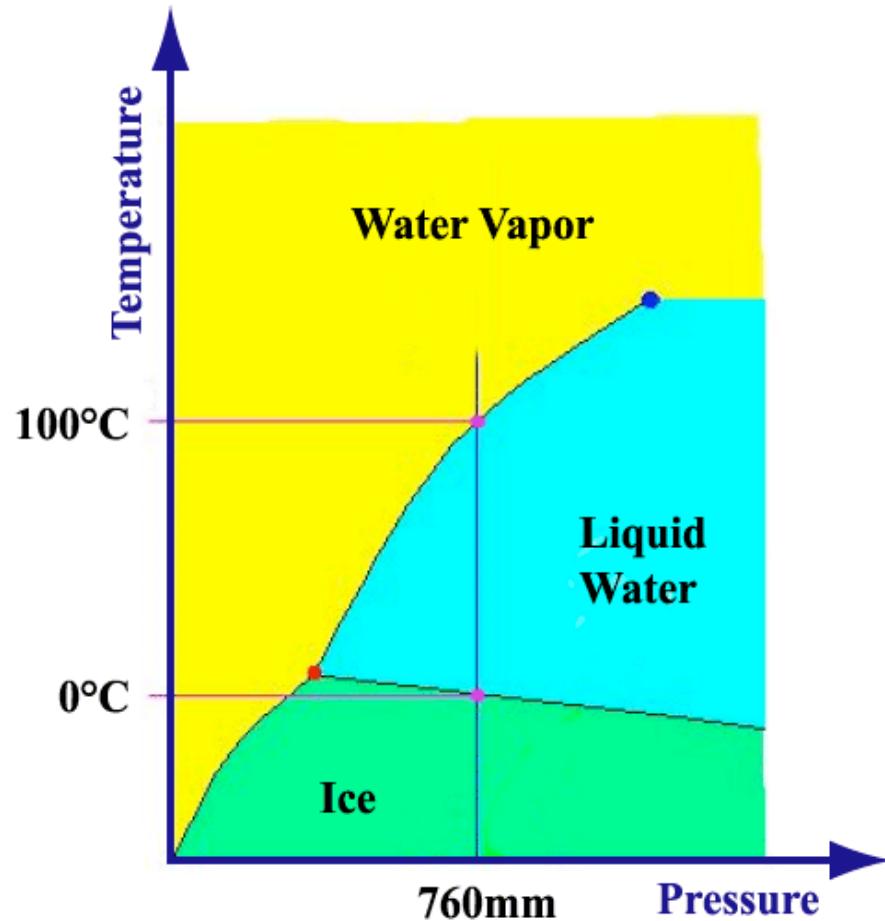
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Outline

- (1) Introduction
- (2) Recent results on the formation of partonic matter at RHIC
- (3) FAiR - **CBM**
- (4) Summary

Phase Structure of Matter



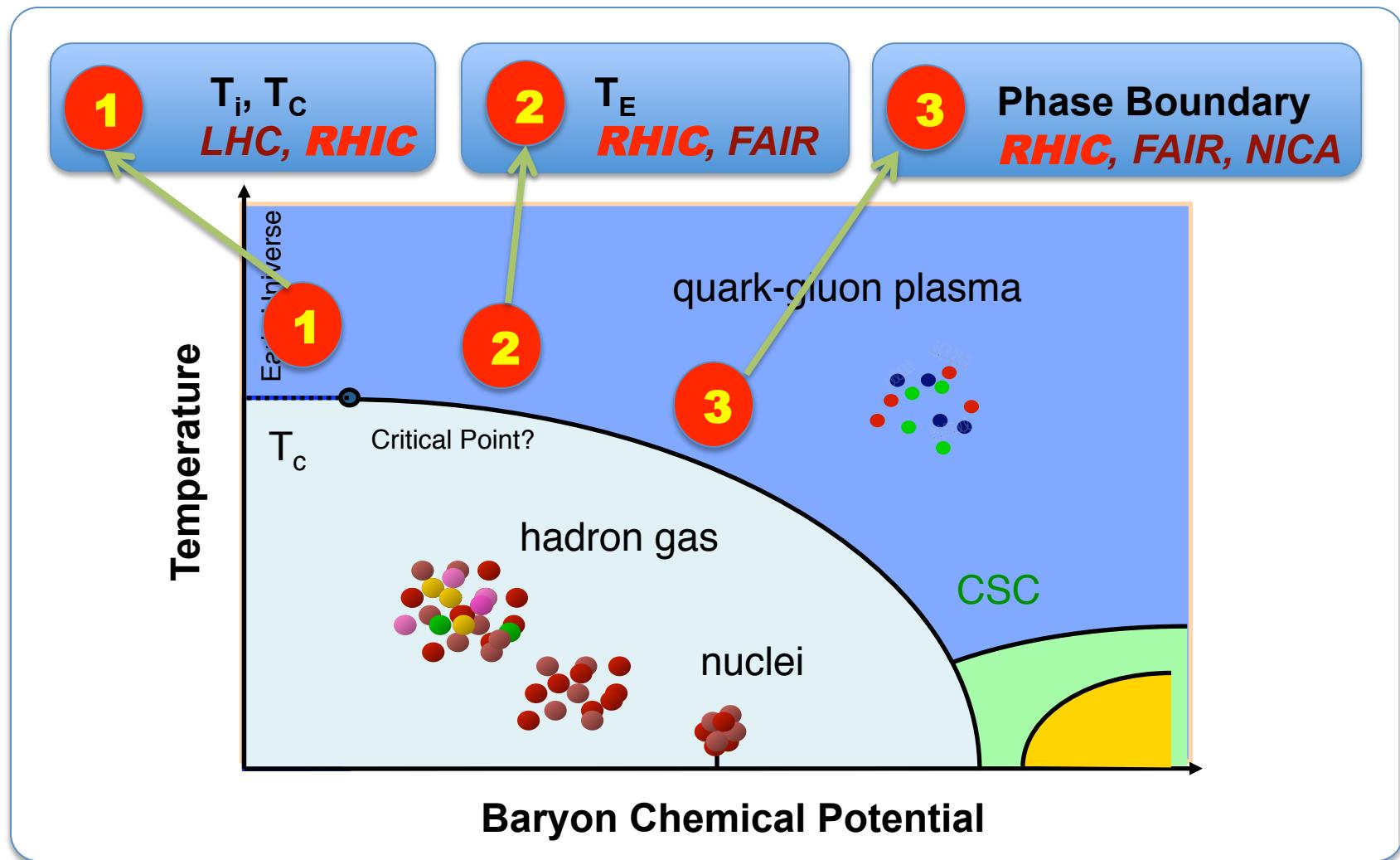
Phase Diagram: How matter organize itself under external conditions.

Water: EM interactions

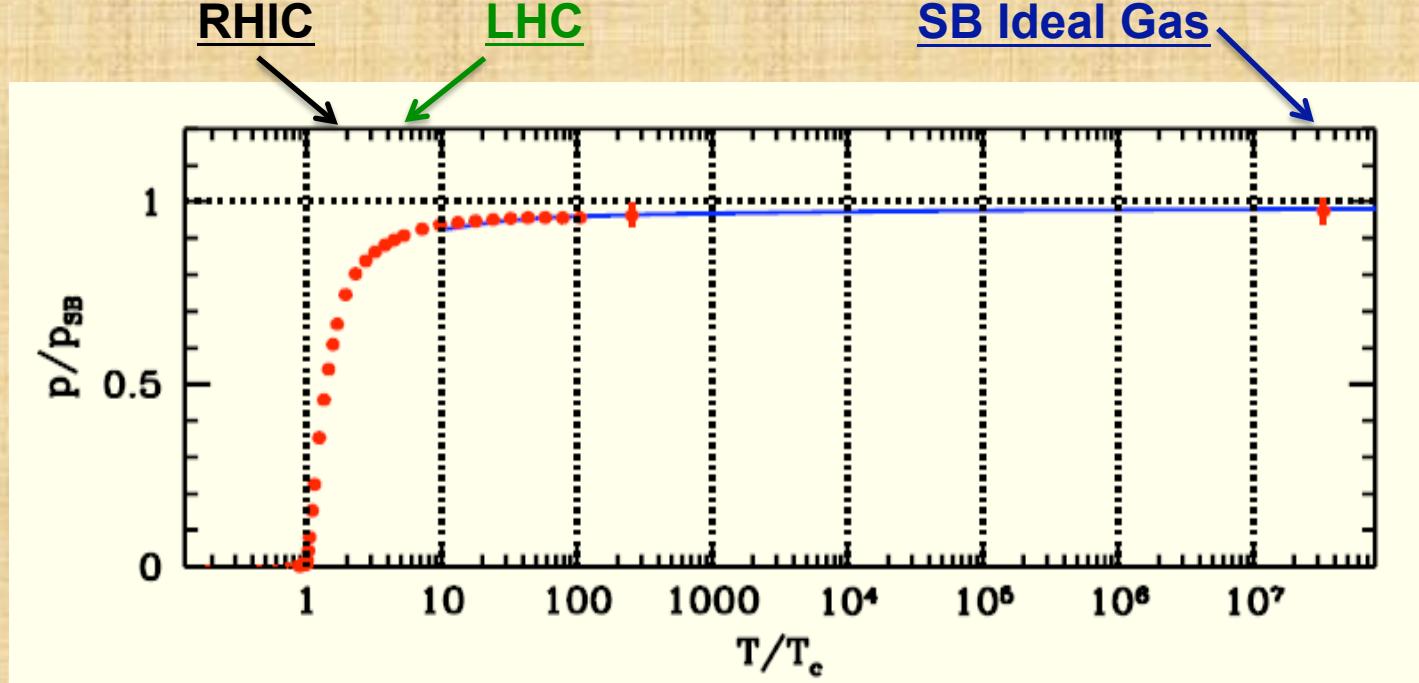
How about strong interaction,
matter with partonic degrees
of freedom?

http://serc.carleton.edu/research_education/equilibria/phaserule.html

The QCD Phase Diagram and High-Energy Nuclear Collisions



QCD Thermodynamics



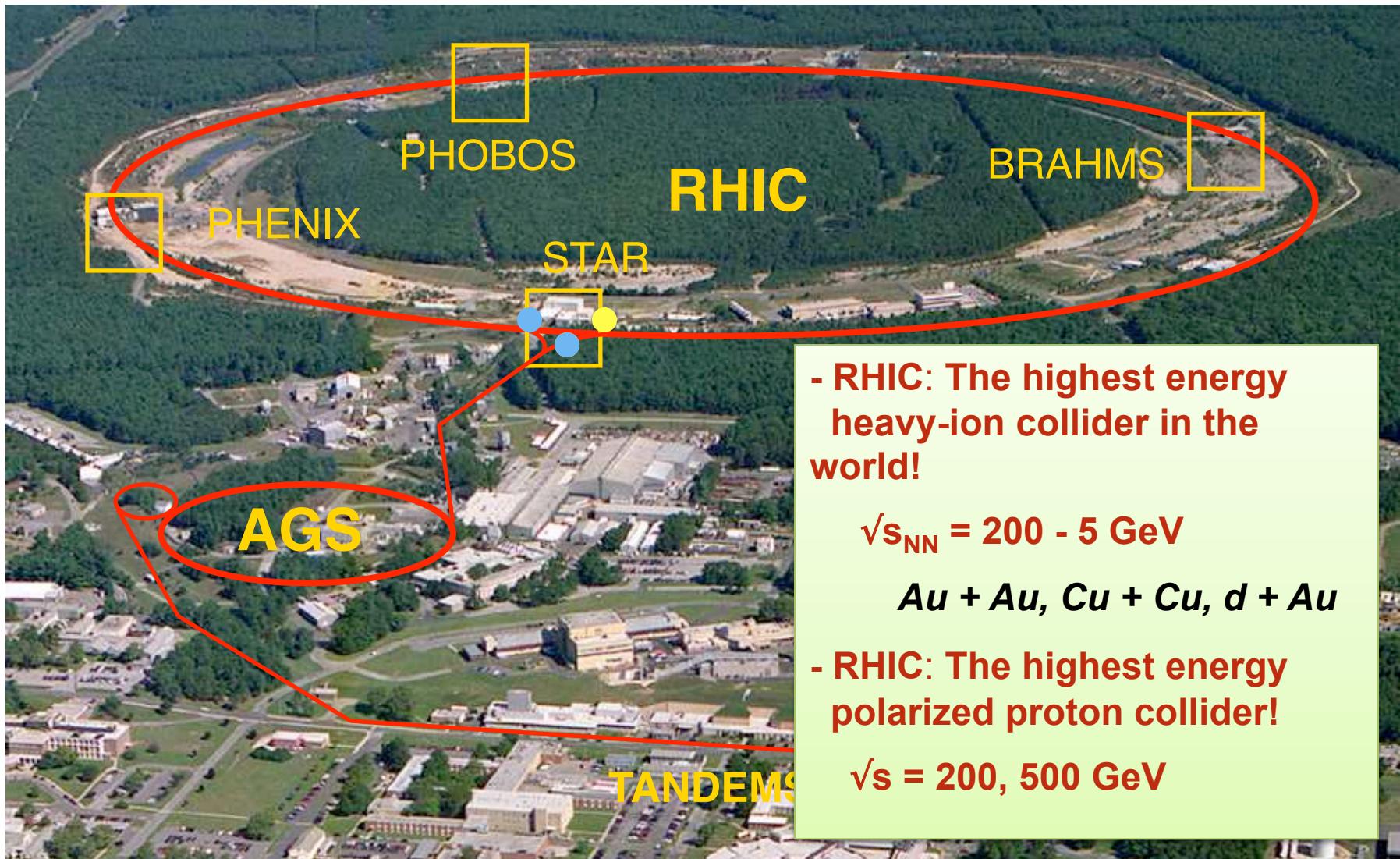
- 1) At $\mu_B = 0$: cross over transition, $150 < T_c < 200$ MeV
- 2) The SB ideal gas limit: $T/T_c \sim 10^7$
- 3) T_{ini} (LHC) $\sim 2\text{-}3 \cdot T_{ini}$ (RHIC)
- 4) Thermodynamic evolutions are similar for RHIC and LHC

Zoltan Fodor, Lattice 2007



Relativistic Heavy Ion Collider (RHIC)

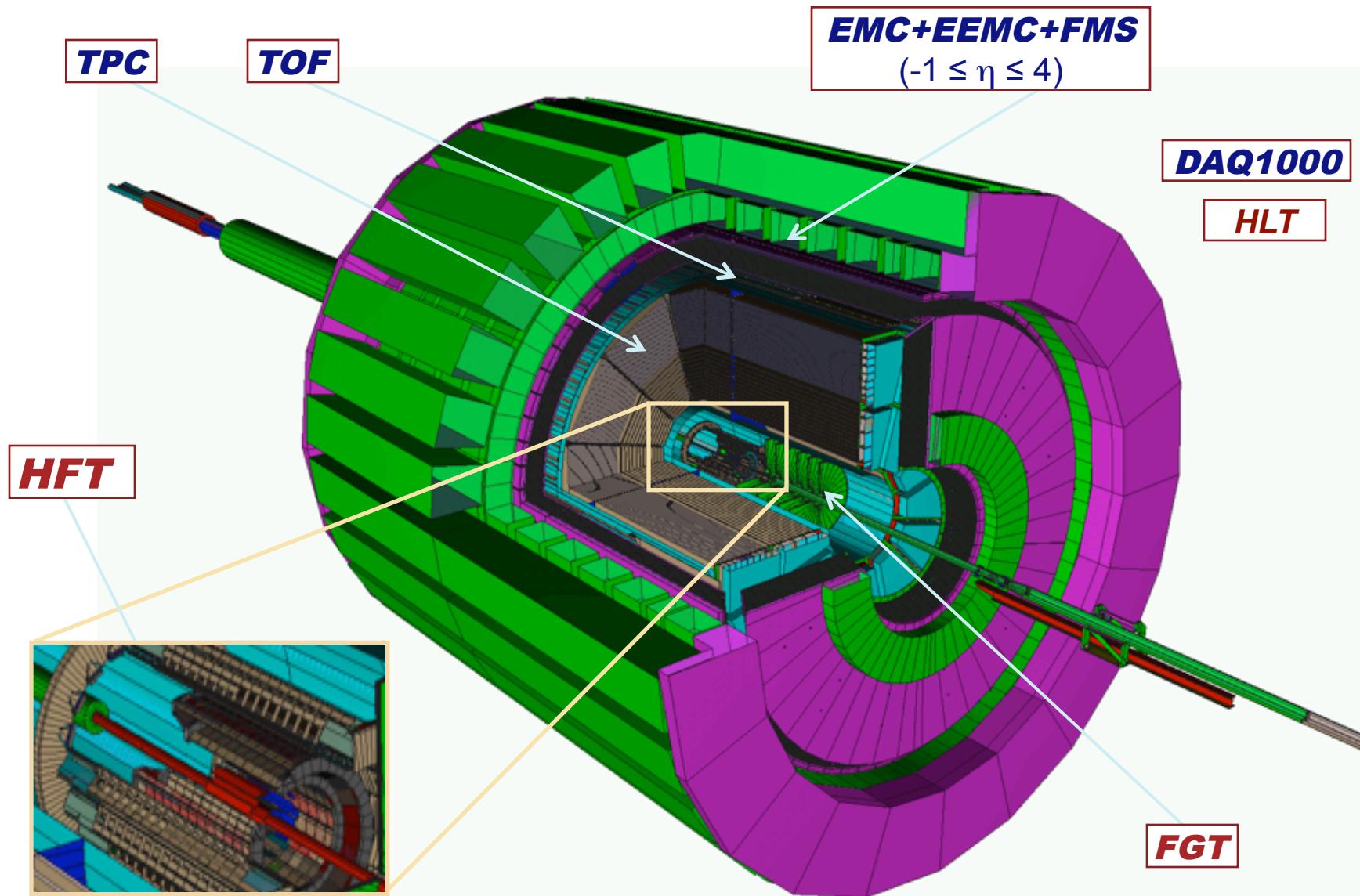
Brookhaven National Laboratory (BNL), Upton, NY



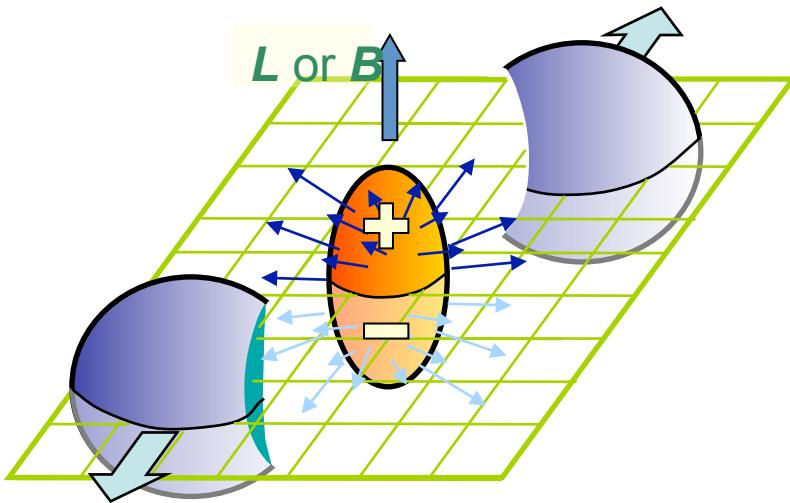
Animation M. Lisa



STAR Detectors: Full 2π particle identification!

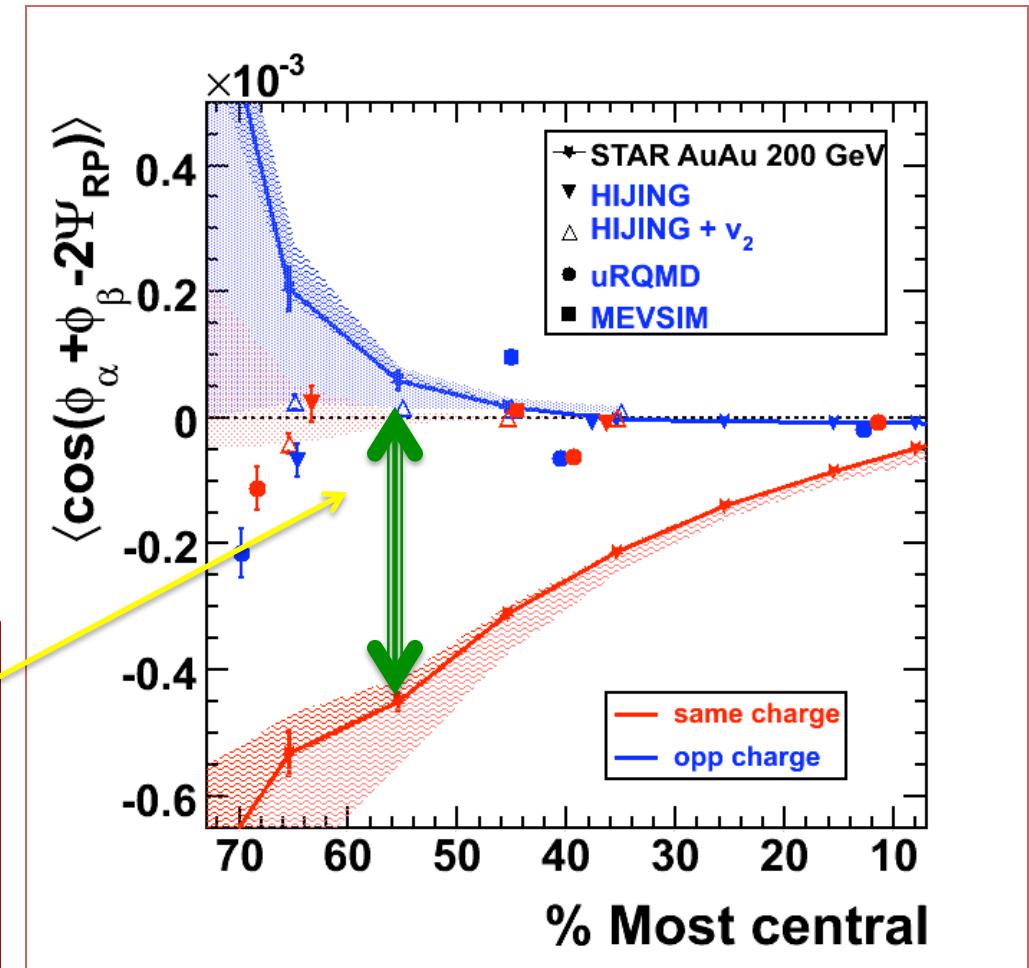


Search for Local Parity Violation



The separation between the same-charge and opposite-charge correlations.

- Strong EM fields
- De-confinement and Chiral symmetry restoration



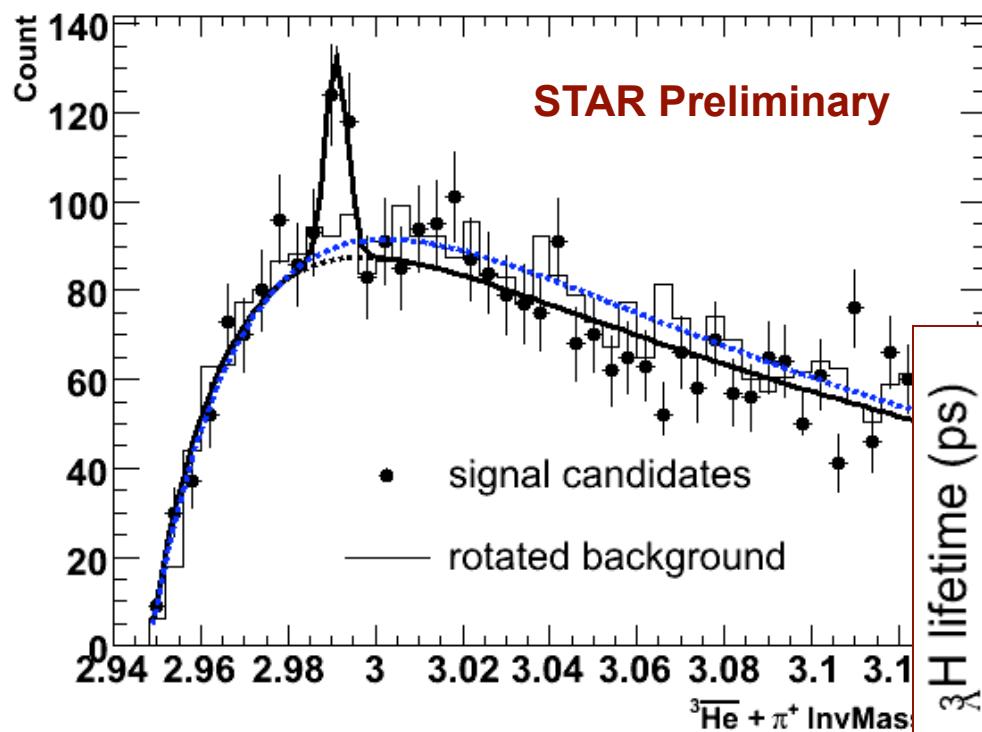
Voloshin, PR C62, 044901(00).

STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).



First Observation of $\bar{\Lambda} \rightarrow {}^3\bar{H} e + \pi^+$

AuAu200_Combined_Anti- ${}^3\bar{H}$ _candidate

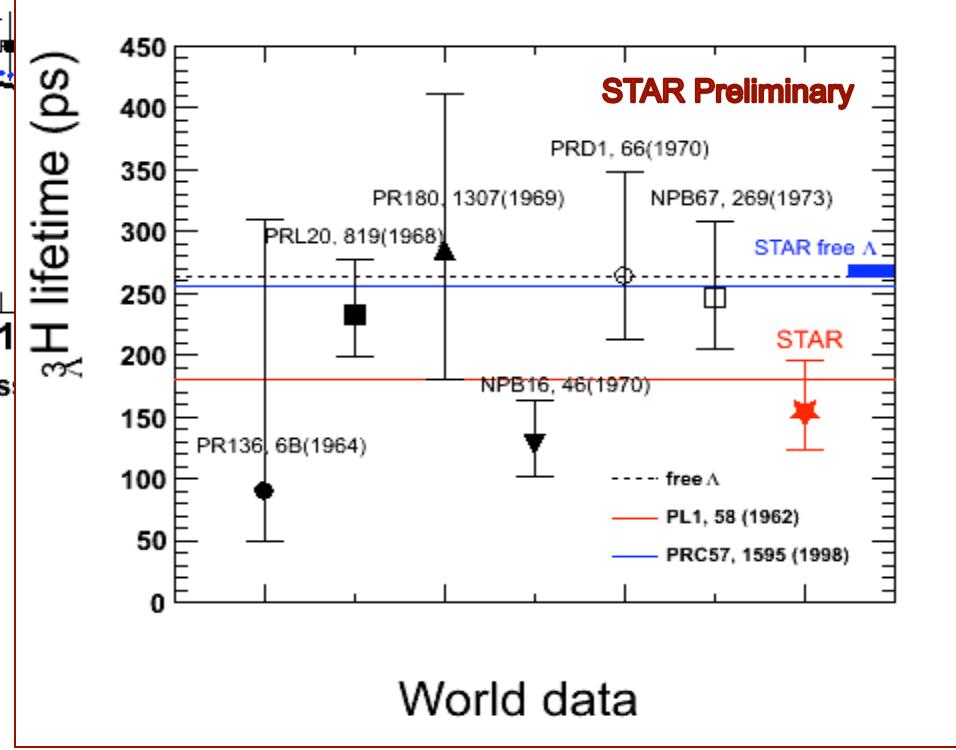


First observation of
an anti-hypernucleus

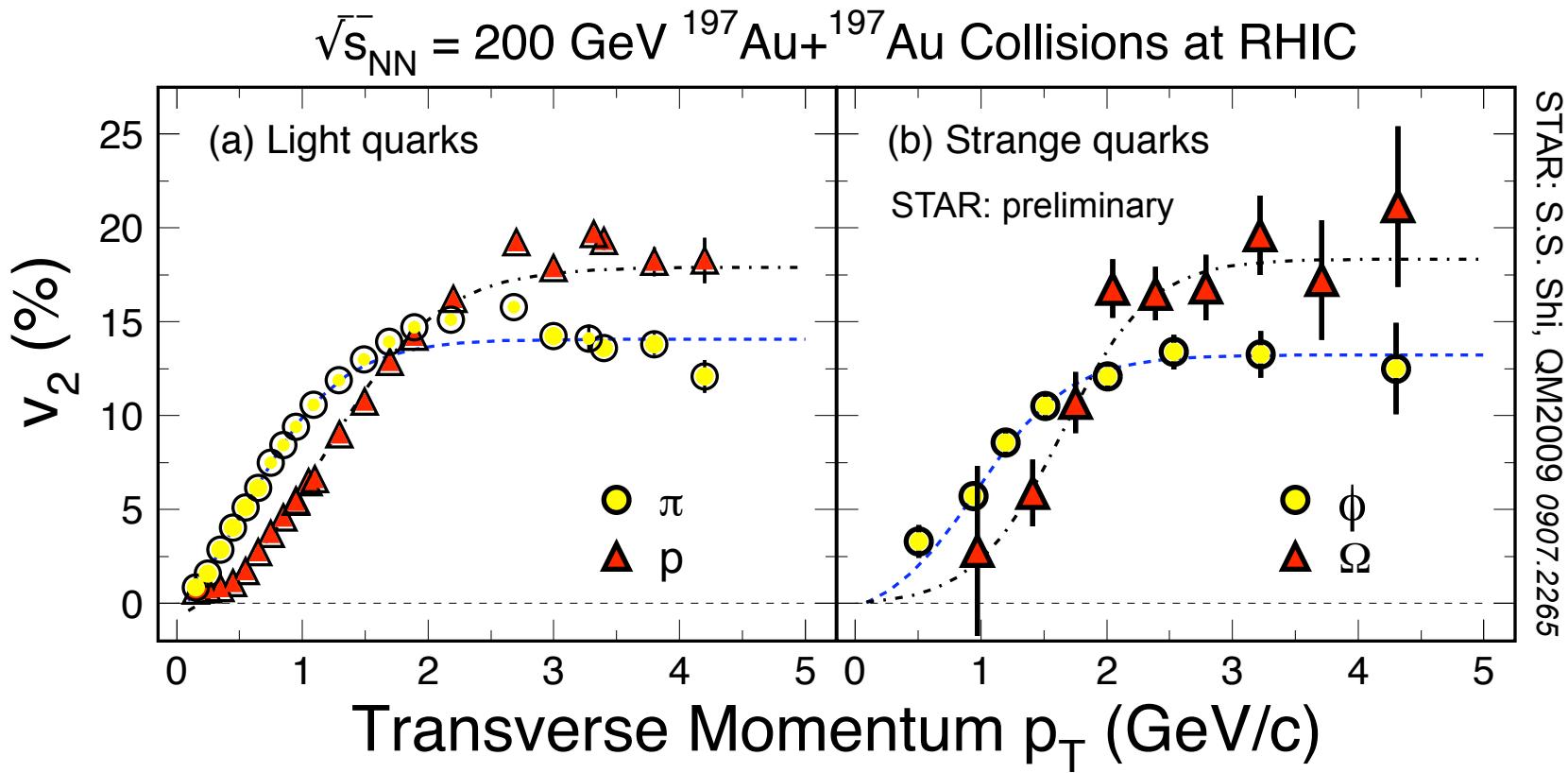
Accepted by the **Science** Magazine

STAR Collaboration, PAs: J. Chen, H. Crawford, D. Keane,
H. Qiu, Z.B. Tang, Z.B. Xu

200 GeV Au+Au collisions at RHIC
- Equilibrium of s-quarks with the rest



Partonic Collectivity at RHIC



Low p_T ($\leq 2 \text{ GeV}/c$): hydrodynamic mass ordering

High p_T ($> 2 \text{ GeV}/c$): number of quarks ordering

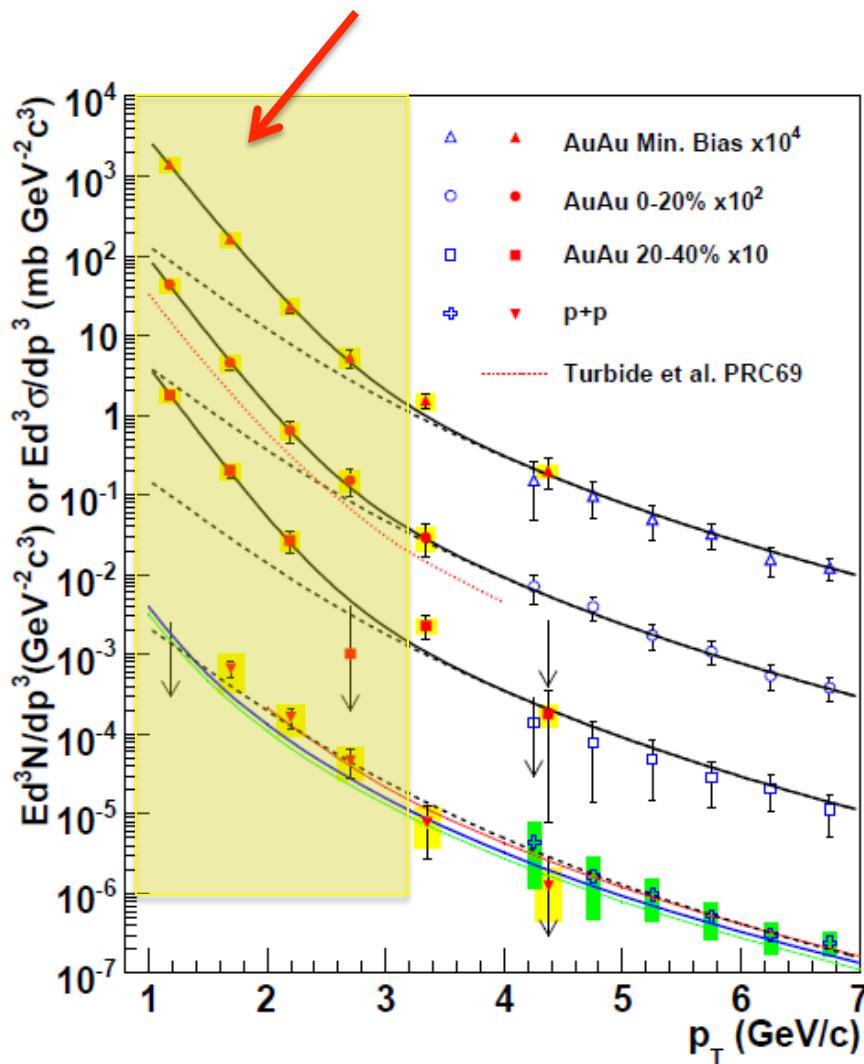
s-quark hadron: smaller interaction strength in hadronic medium

light- and s-quark hadrons: similar v_2 pattern

=> Collectivity developed at partonic stage!

Direct Photon Spectra

QGP thermal radiation



PHENIX direct- γ results:

- real ($p_T > 4 \text{ GeV}$)
- virtual ($1 < p_T < 5 \text{ GeV}$)

pQCD calculations consistent
with p+p to $p_T \sim 1 \text{ GeV}/c$

At $p_T < 2.5 \text{ GeV}/c$, central
Au+Au data are above N_{coll}
scaled p+p result:

$$T_{Au} = 221 \pm 19^{\text{sta}} \pm 19^{\text{sys}} \text{ MeV}$$

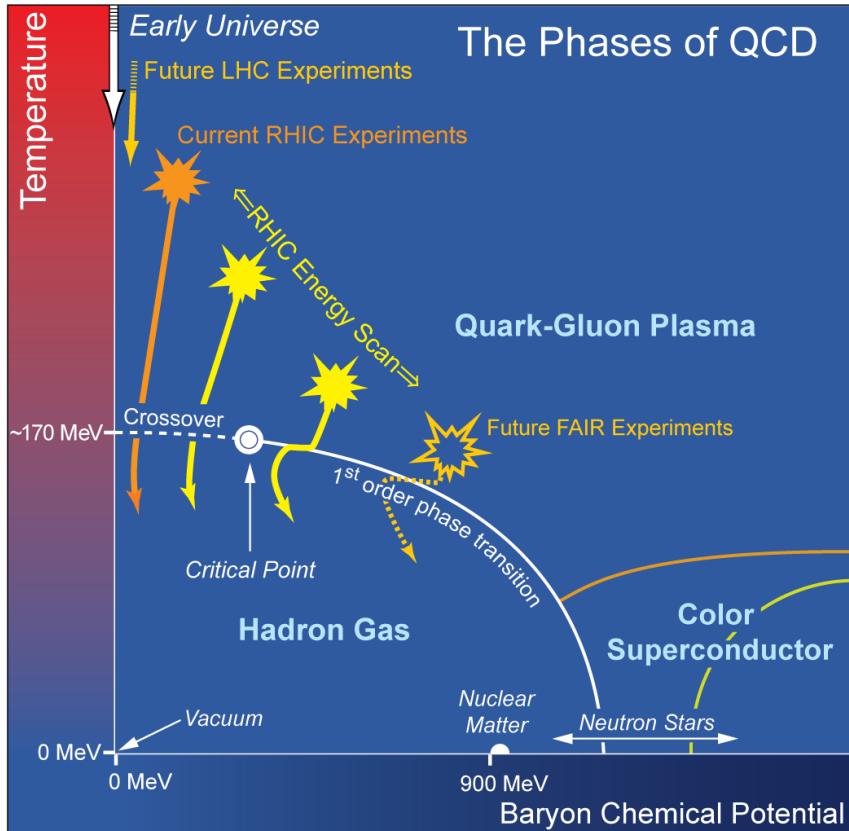
$$T_{ini} = 300 \sim 600 \text{ MeV}$$

$\sim 14 \text{ trillion } {}^0\text{C}$

~ 2500 times center of Sun

A.Adare *et al*, PHENIX, 0804.4168

The QCD Critical Point



RHIC (200) & LHC: Determine the temperature T_{init} , T_c

BES: Explore the QCD phase diagram T_E and the location **phase boundary**

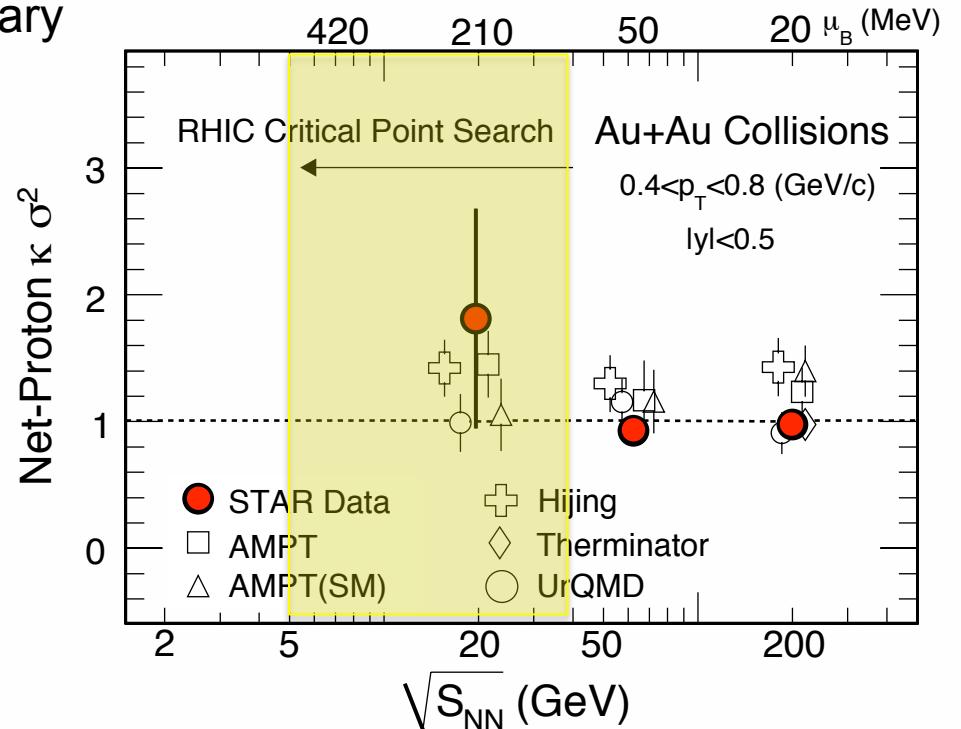
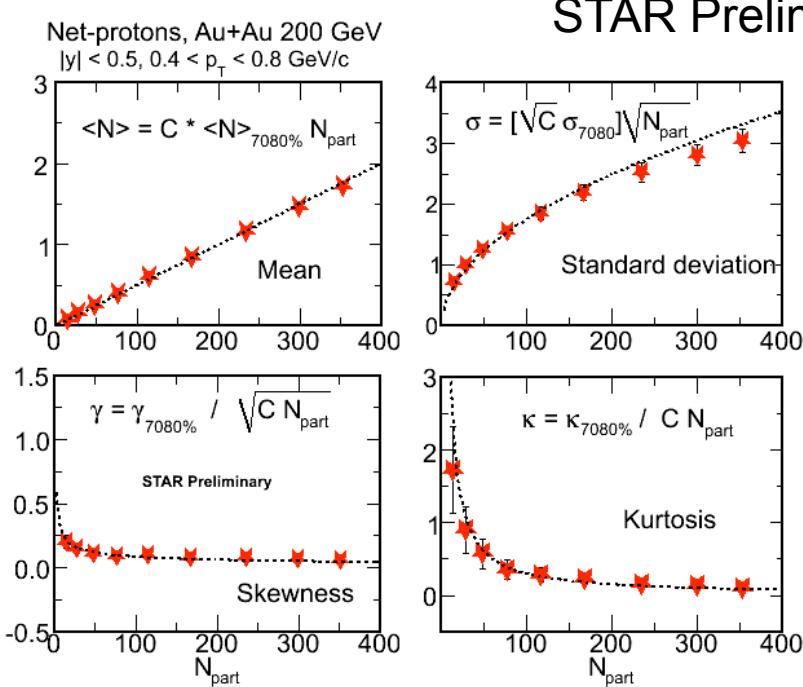
- LGT prediction on the transition temperature T_c is robust.
- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.
- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

* *Thermalization has been assumed*

M. Stephanov, K. Rajagopal, and E. Shuryak, *PRL* **81**, 4816(98); K. Rajagopal, *PR* **D61**, 105017 (00)

<http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf>

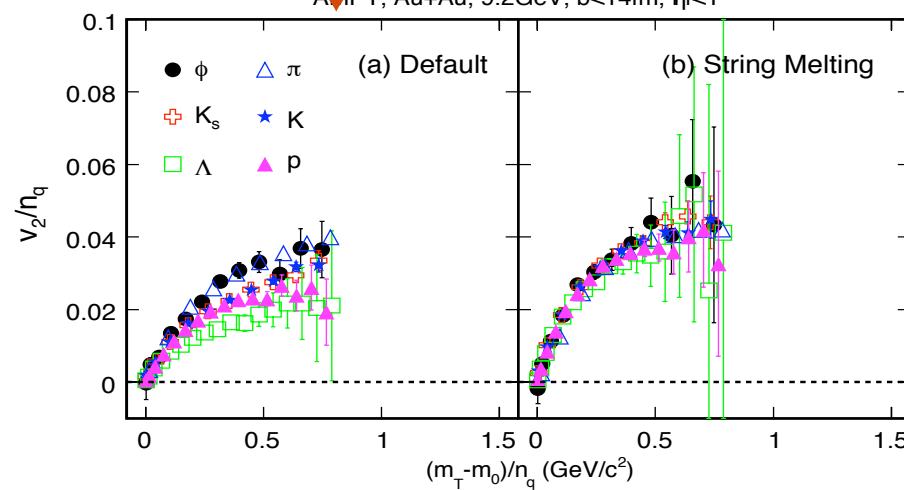
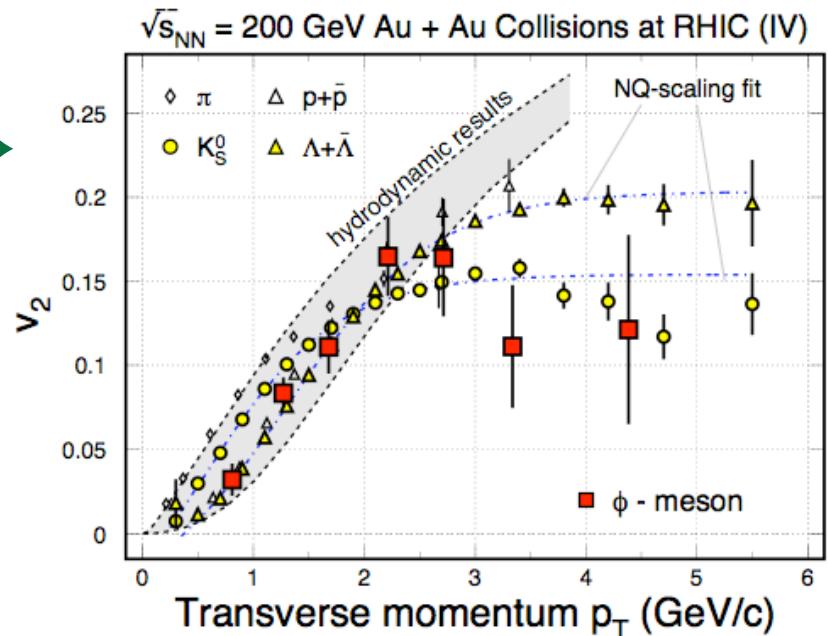
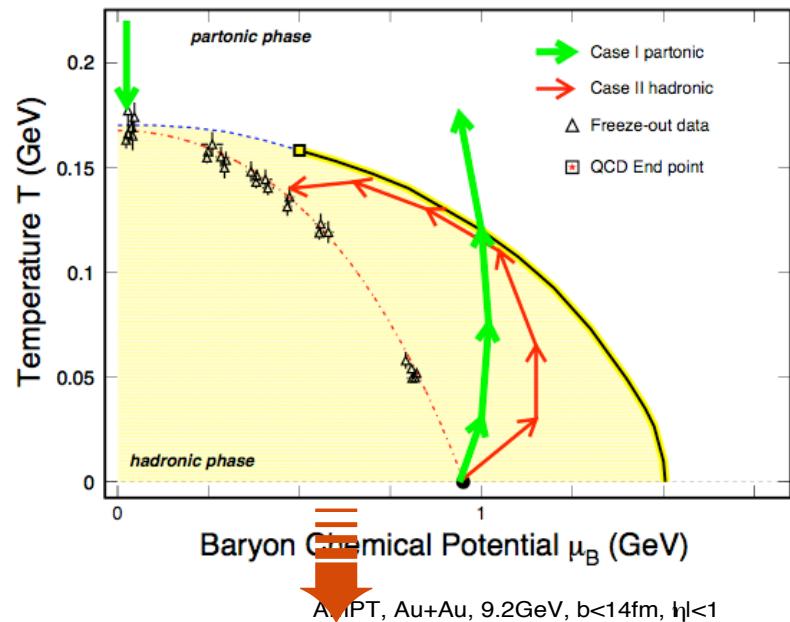
High Moment Analysis (BES)



- 1) High moments are more sensitive to critical point related fluctuation.
- 2) The 4th moment, Kurtosis, is directly related to the corresponding thermodynamic quantity: susceptibility for conserved quantum numbers such as Baryon number, charge, strangeness...

STAR Collaboration: X.F. Luo, B. Mohanty, H.G. Ritter ...

Observable*: Quark Scaling in v_2



STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $s\bar{s} \Rightarrow \phi$ not $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of ϕ will be small.

* Thermalization is assumed!



Run10 Physics Programs

RHIC cool down mid-Nov.

Cool down to 4.5°K: Dec. 1; Shift starts Dec. 7; Data taking: Jan. 2

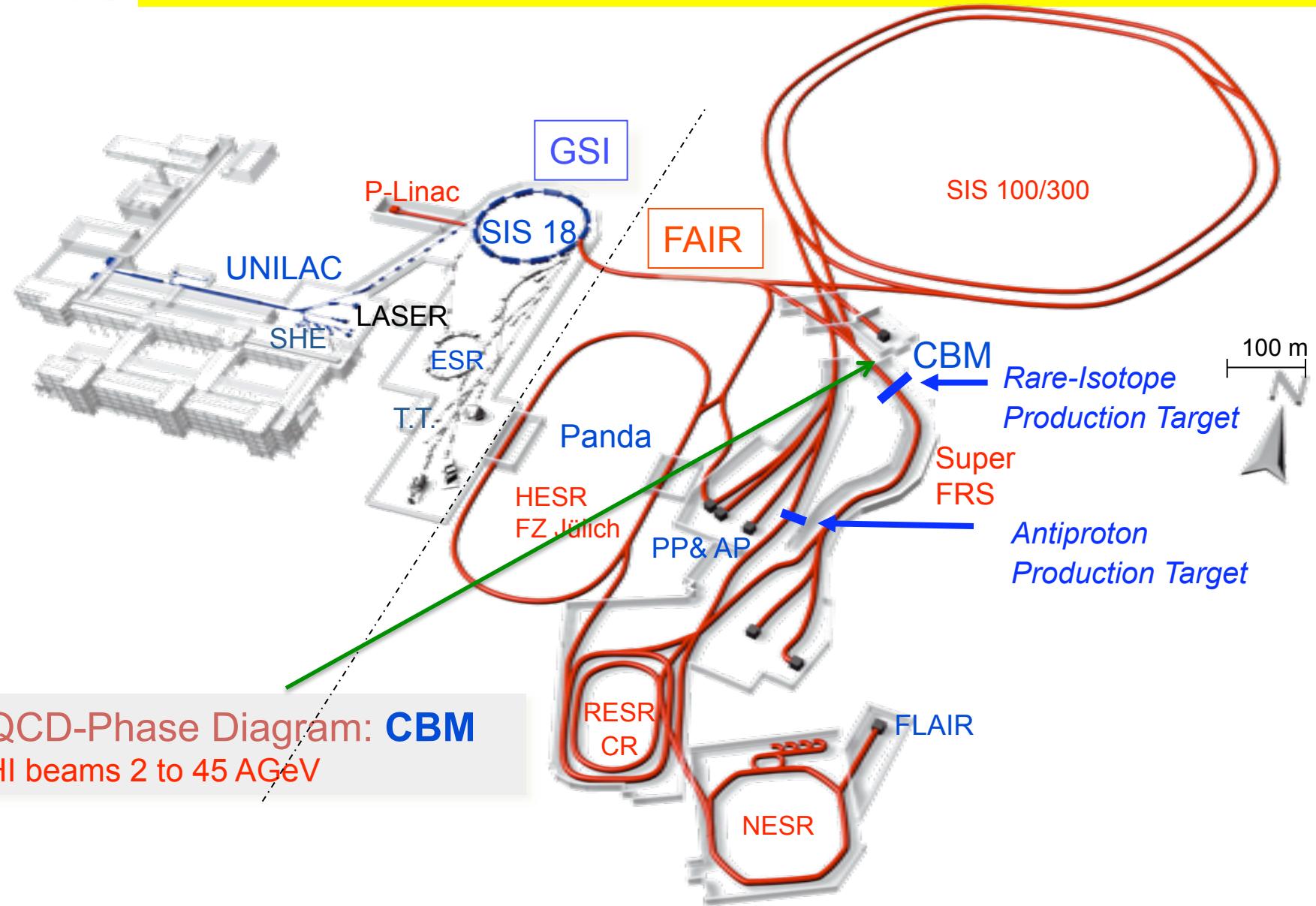
Shift committee: O. Barannikova

Trigger board: Z.B. Xu (*chair*)

QA board: C. Whitten (*chair*)

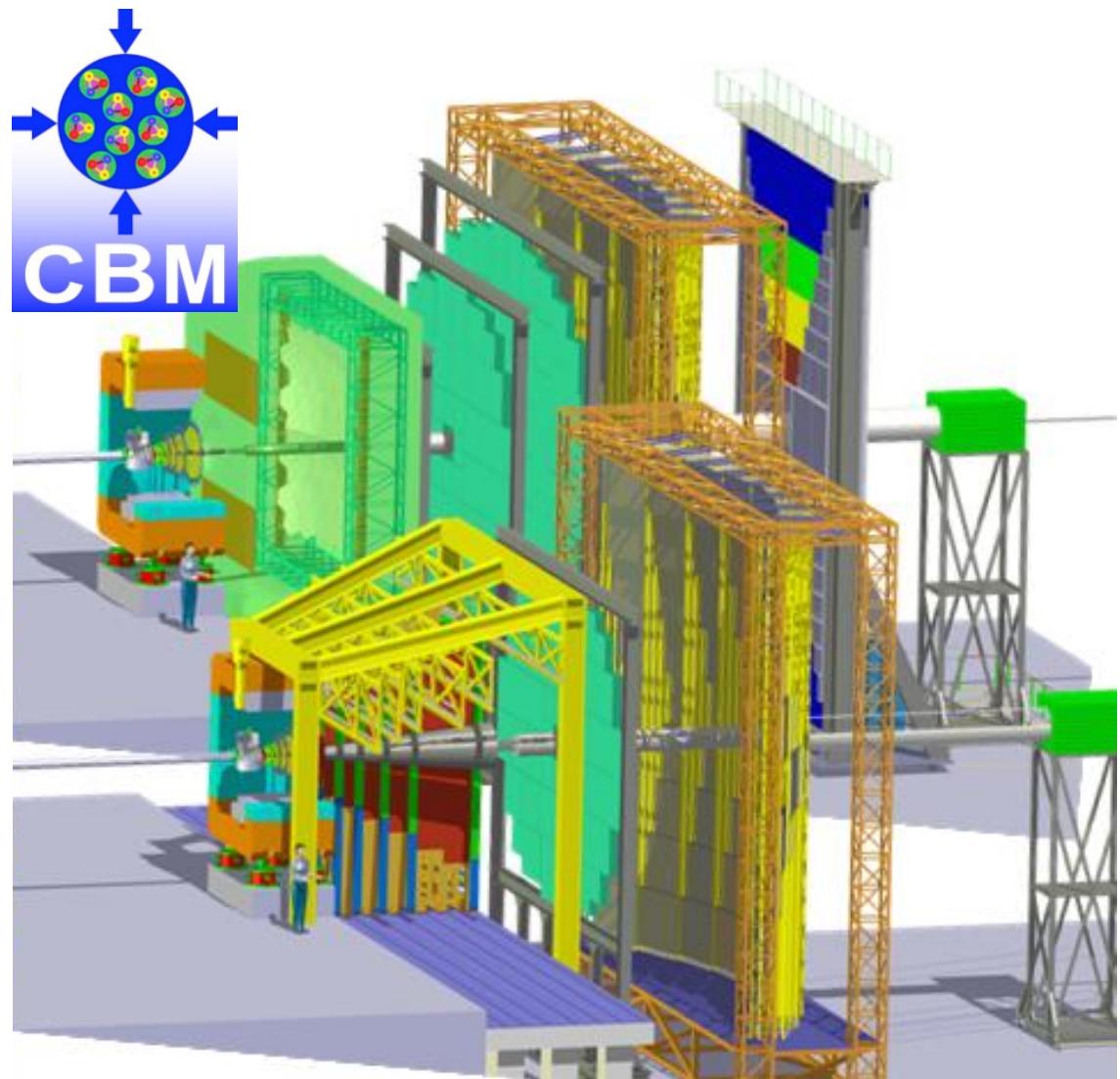
Beam Energy (GeV)	25 cryo-week	30 cryo-week	Physics
200	10 3/16	10	Thermalization $J/\Psi v_2, m_{ee}$
62.4	4 4/15	4	
39	1.5 4/28	1.5	
27			
18			
11.5		2 6/19	BES programs, T_E , phase boundary
7.7	4 5/25	4	
5.5	0.5 5/28	0.5	

Weekly info: http://www.c-ad.bnl.gov/esfd/RMEM_10/rhic_planning.htm

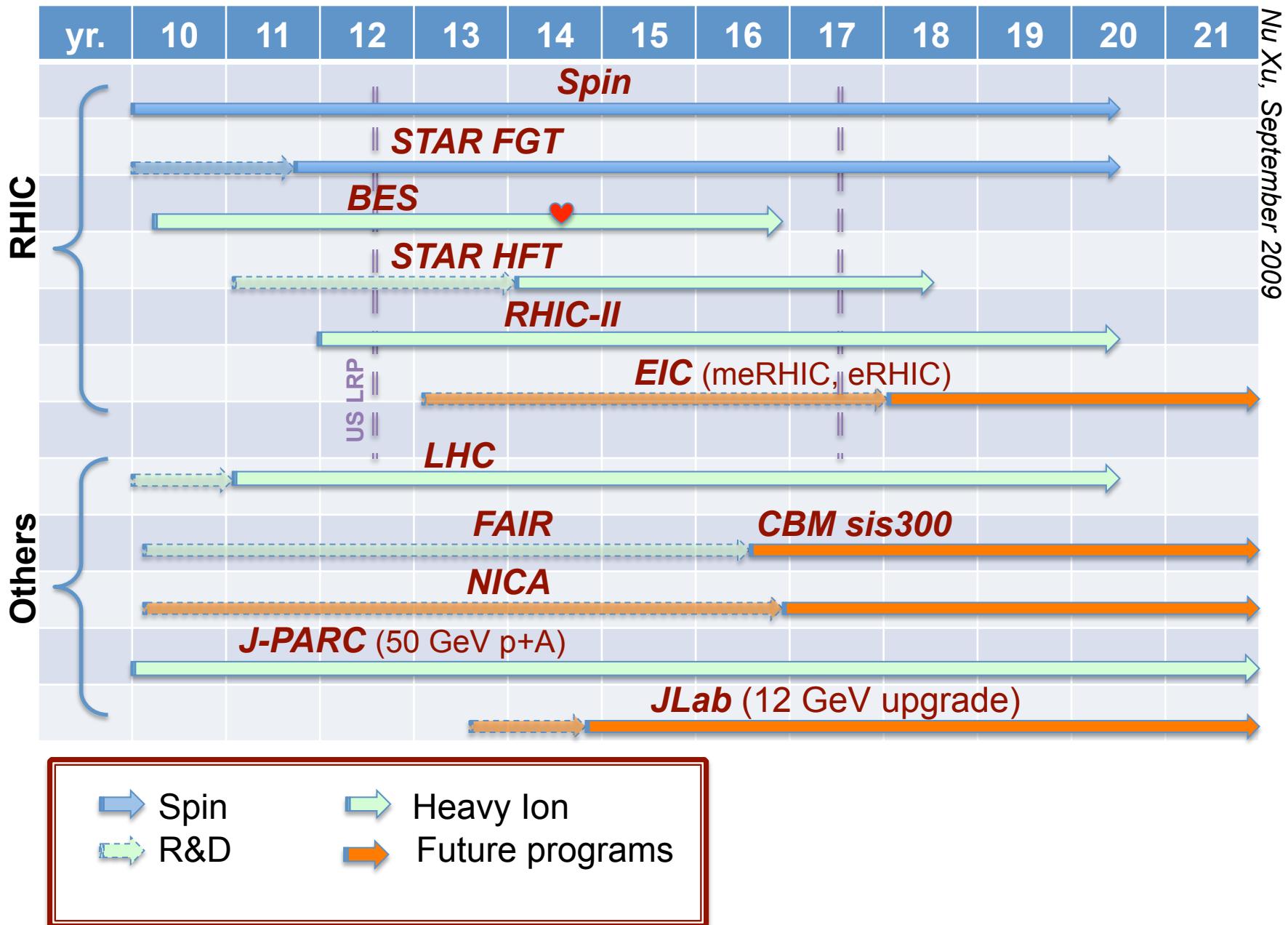


The Compressed Baryonic Matter Experiment

- Exploration of the QCD phase diagram at **highest baryon densities**
- Experimental focus on **rare diagnostic probes**
- **High-rate detectors with free-streaming readout and online event selection**



Timeline of QCD and Heavy Ion Facilities



Summary

- 1) New form of matter with partonic degrees of freedom: evolution of the universe, nuclear phase diagram, critical point, ...
- 2) FAIR: New, international, exciting endeavor for the next few decades' collisions physics.
- 3) Pushing both Science and Technology fronts